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A survey on energy storage resources configurations in order to propose an optimum configuration for smoothing fluctuations of future large wind power plants

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ABSTRACT

As the wind power capacity increases, the effect of wind power fluctuations on the system stability becomes more significant. Despite its high costs, utilizing energy storage resources such as batteries is inevitable in the smoothing process of wind power fluctuations. In a wind power plant, the place where batteries are located has considerable direct effect on their required capacity and thus on the initial investment cost. Therefore, in this paper a suitable configuration which significantly reduces the batteries investment cost is proposed and then the wind power fluctuation of a large wind power plant connected to a smart distribution grid is smoothed. Additionally, existing configurations for installing batteries in large wind power plants are investigated. The proposed configuration utilizes smart parks as aggregated storage resources in load side and an aggregated battery energy storage system with limited capacity in plant side as well. Therefore, in addition to accurate smoothing of wind power fluctuations, the energy storage investment cost is reduced significantly utilizing the proposed configuration. Simulation studies in MATLAB software package are carried out to verify the performance of the proposed approach.

Contents

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1. Introduction

Nowadays, the environmental organizations force for decreasing the levels of greenhouse gases, the global warming, and increasing demand for electrical power along with increasing in the price of electrical power has directed the attention of different governments to renewable electrical resources. Wind is one of the renewable resources having advantages that specify it from other kinds of renewable energies [1]. Firstly, the primary resource of the wind is abundant everywhere inshore or offshore. Secondly, compared with other resources like solar energy, the investment cost in wind power is relatively low. Furthermore, the bioenvironmental quality of wind turbines is satisfying as compared with traditional energy resources. However, the increasing use of the wind energy in electrical grids along with the power generation increase in Wind Power Plants (WPPs), has made some new issues in power networks [2].

Regarding their high cost compared with other parts in power generation system, wind turbines should be designed to work in the Maximum Power Point Tracking (MPPT) [3]. In this case the output power of Wind Turbine Generators (WTGs) always fluctuates because of the random nature of the wind speed [4]. The increase in WPP capacity makes the impact of Wind Power Fluctuations (WPF) on the system stability more considerable and even may lead to power system collapse in unsuitable situations [5]. A traditional solution to smooth the fluctuations is to sell the surplus wind power in competitive market or purchase traditional power to compensate the shortage of the wind power generation. However this solution is not acceptable from two viewpoints; first, during the compensation process the bioenvironmental contamination increases by thermal units. Second, purchasing with no anticipation causes extra costs. Facing such challenges, energy storage technology, which can be regarded as the most promising solution for wind energy, can relieve and even eliminate such issues. Actually, energy storage technologies have been already investigated extensively and successfully in other high-CO_2 emission areas, such as heating, ventilation, and air conditioning for industry, commercial and residential applications [6–8]. Therefore, Battery Energy Storage System (BESS) can be an efficient way for WPF smoothing in spite of a little higher cost of batteries [9]. The location of in-service batteries in WPP has a considerable direct effect on their required capacity and therefore on the initial investment cost. Thus, there are different configurations for emplacing batteries in a WPP. For example, it is possible to use a single BESS for each WTG, or a BESS for a set of WTGs, or a BESS with a suitable capacity for the whole WPP. The location of BESS affects the required BESS capacity for the whole system and thus influences the initial investment cost. So far, different surveys have been conducted on this subject.

A review of different methodologies for solving the problem of wind power fluctuations has been presented in [10]. Energy storage system technologies and configurations used in a wind farm have been compared in [11,12]. Simulation results of the comparison between aggregated ESS configuration and distributed ESS configuration have been shown in [13]. Another configuration using aggregated ESS in load side has been presented in [14]. Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications has been studied in [15].

Indeed, in order to smooth wind power fluctuations a large number of methods have been proposed in [16–18], however they have mostly concentrated on coordinated control methods rather than proposing a new configuration.

The optimum configuration is the one that minimizes the investment cost required for BESSs in addition to performing an appropriate smoothing for WPP output power. A useful solution is to utilize electrical smart grids. Electrical smart grid is a power network with a combination of thermal plant and renewable energy resources utilizing Information Technology (IT) and communicational infrastructures in order to considerably improve the quality and safety of generation, distribution and consumption of the electrical energy [19]. These networks have introduced new phenomena like Smart Parks (SPs) having an important part as a very huge battery in reducing WPF [20–23]. In order to minimize the investment cost of batteries, in this paper the existing configurations for installing batteries in large WPPs are studied and compared, then a suitable configuration is presented which makes it possible to smooth the fluctuations of a large WPP with a considerable power as much as possible. Also utilizing the available energy storage equipment such as SPs in a smart grid is considered.

The rest of the paper is organized as follows: the output power fluctuations of a WTG and a WPP are illustrated in Section 2. ESS configurations for WPP are described in Section 3. In Section 4, SPs are introduced as huge batteries in smart grids. The proposed configuration is presented in Section 5. In Section 6 the under-study network is introduced first and then the modeling procedure of WTG, WPP and SP, implementation of the proposed configuration and comparing it with two other methods are described respectively. Section 7 draws the conclusion and finally the references are presented.

2. Fluctuations resulted from large WPPs

As explained in the previous section, because of high final costs of wind turbines, they need to work in MPPT in order to justify the costs by extracting the maximum power. On the other hand, wind is a totally random fluctuating resource. So it is evident that the output power of a WTG always fluctuates. For instance, the output of a Doubly Fed Induction Generator (DFIG) wind turbine with a nominal capacity of 5 MW for the applied wind with an average speed of 14 m/s has been illustrated in Fig. 1. It is clear from this figure that a typical WTG may have fluctuations up to 60% of its nominal power (in the case of using no BESSs at all).

But how about the WPF of a medium WPP with a 500 MW capacity? Fig. 2-a illustrates fluctuations of a 500 MW WPP (network characteristics and modeling information have been given in Section 6). In this study, WPPs with 100, 500 and 1000 MW capacity have been considered as small, medium and large WPPs respectively. WPF of this WPP is about 20% of its nominal power. If the modeling of the WPP is not precise and the whole WPP is modeled only by one single WTG, the resulted amount for fluctuations will be 60% leading to a wrong result. Indeed, the delay of wind blowing to different WTGs helps them to moderate the fluctuations and thus the output power of the whole WPP gets less fluctuation compared with that of one single WTG. As the WPP capacity goes higher, the fluctuation percentage decreases. Fig. 2-b shows the WPF of a WPP with a capacity of 1000 MW. In this case, the fluctuations diminish to about 14% (notice that

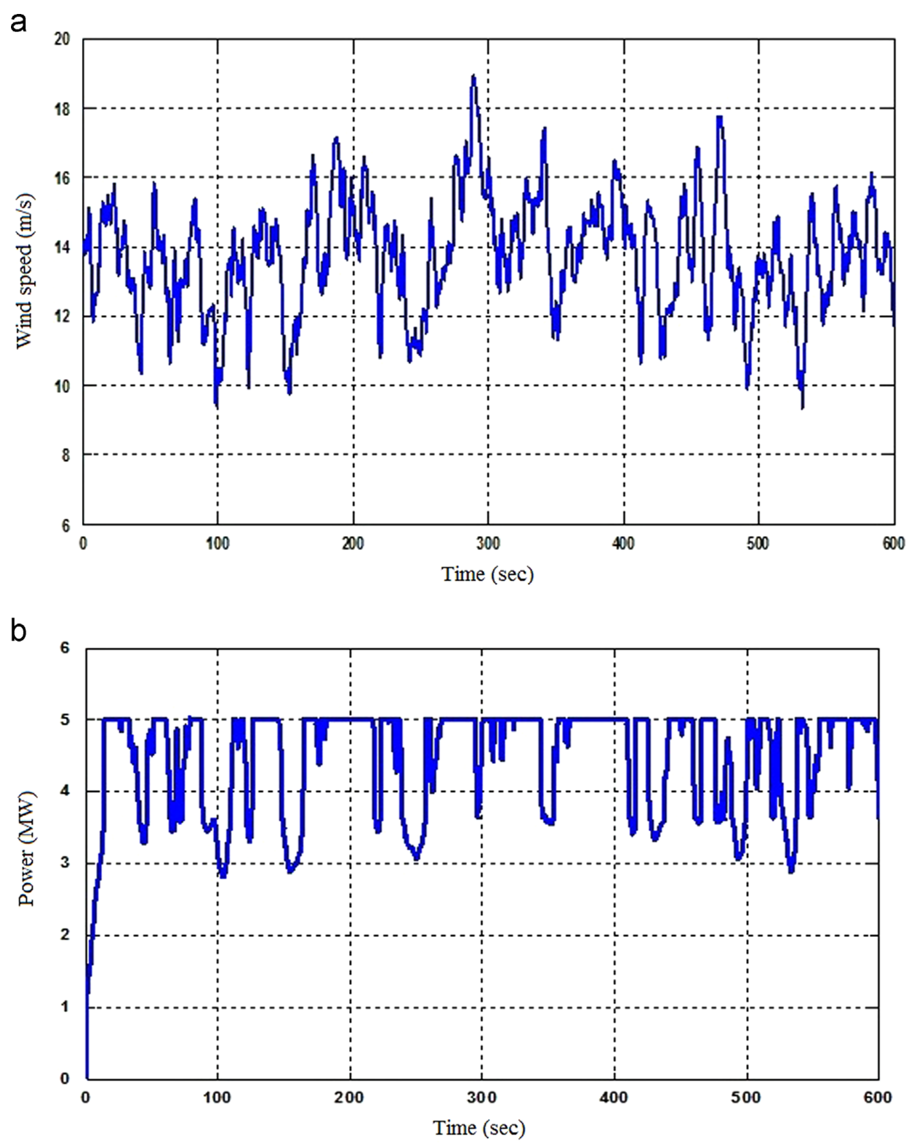

Fig. 1. (a) Wind speed with an average speed of 14 m/s and (b) the output power of a 5 MW DFIG WTG.

the average power in the shown interval is 700 MW). This is the reason which encourages operators to construct larger WPPs. Because the larger the WPP is, the lower the fluctuation will be, and this contributes to reduction of BESS cost. It is worth mentioning that this remained 14% fluctuation of a large WPP still needs to be saved in high capacity storages and this leads to a high initial investment cost. Therefore, utilizing the wind energy can be easier if the solution to the reduction of storage costs is discovered.

3. Configuration of BESS for a WPP

In a WPP, BESS can be configured as an aggregated unit serving the whole WPP or it can be distributed in a way that in each single WTG there is an installed BESS. Both configurations have been shown in Fig. 3 [11]. In some other configurations, there are several integrated sections serving a group of WTGs.

The performance difference of BESS in different types of configurations has been rarely taken into account in manuscripts. Because of the smoothing effect of WTG spatial distribution, the fluctuation of total WPP power is lower than that of every single WTG power. Hence, the performance of aggregated BESS is better than that of distributed BESS in an equal capacity situation. The accuracy of this assumption has been verified in [11] at a simplified condition.

Another configuration presented for improved smoothing of output power in a WPP is the use of distributed BESSs in load side rather than aggregated BESS in WPP side. Authors in [24] studied both configurations and found out that distributed BESS configuration in load side is preferable for smoothing applications. Fig. 4 shows distributed BESS configuration in load side.

4. SPs as huge batteries

Nowadays, emerging smart grids has involved many research contents in technologies related to them. These researches mostly concentrate on definition, infrastructure design, centralizing distributed generation, combination of advanced IT strategies, etc [25–27]. Smart grids can improve the integration of renewable energy resources with traditional centralized power systems.

SPs are sets of Plug-in Electric Vehicles (PEVs) located in a parking lot. Indeed, these parking lots are based on communicational infrastructures [28]. Various applications have been proposed for PEVs. One example is to buy the electricity from vehicles during

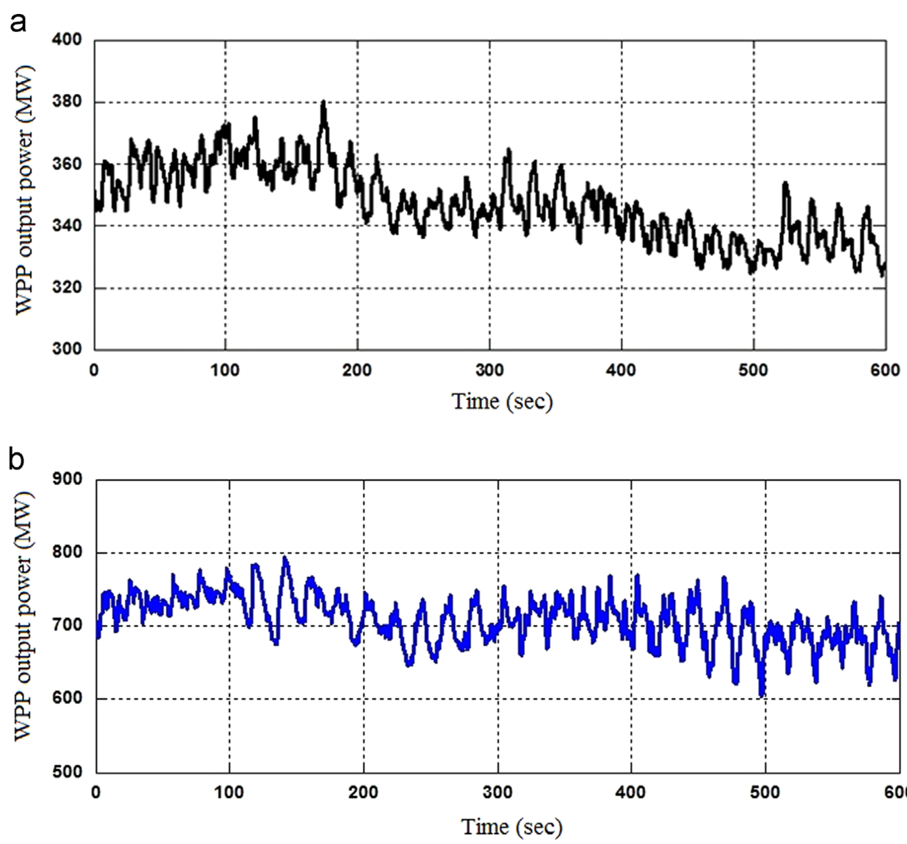

Fig. 2. WPP output power: (a) 500 MW and (b) 1000 MW.

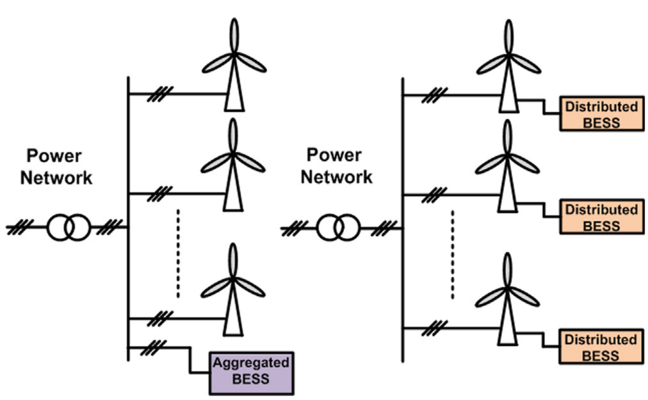

Fig. 3. Aggregated (left) and distributed (right) BESS configuration in WPPs.

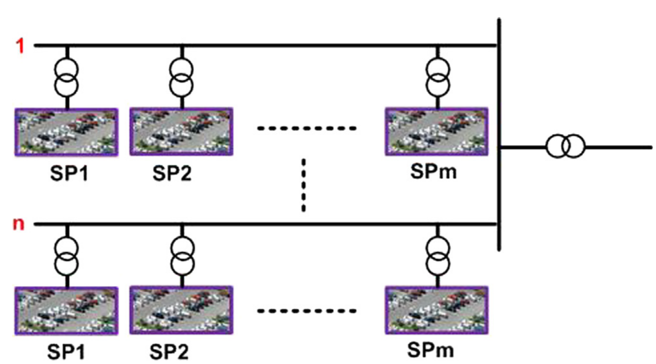

Fig. 5. The configuration of SPs in city.

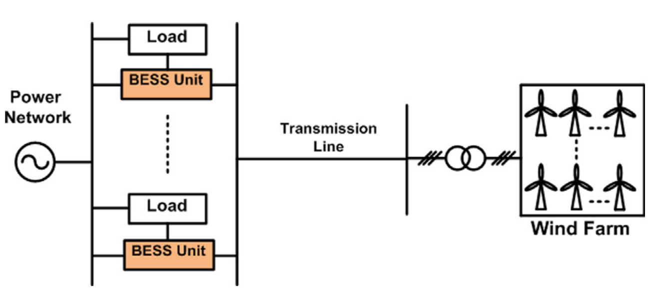

Fig. 4. Distributed BESS configuration in load side.

low load hours for a lower price and sell it during the peak hours for a higher price [29]. This application is beneficial and can be carried out in parking place at home. Another application is in big cities for smart distribution grids. In fact, SP is a set of hundreds or thousands of PEVs forming a very big battery altogether. By combining SPs, an enormous energy storage system is created. As a PEV enters a SP, all of its data including battery capacity and initial charge state is received (via wireless system or any other technology) by the parking lot system. Thus, the storage capacity of the park varies all the time. Received data is sent to the central control system of SPs by the related SP control system. Therefore, the charging/discharging capacity of the whole system is definite for every moment. These parks are scattered in the city and are combined to each other by a bus as in Fig. 5.

In near future, the conversion of usual parking lots to SPs will provide important capabilities for smart distribution grids. As a typical example, Fig. 6 illustrates the diagram for the number of parked cars in a usual parking lot in Tehran (Beihaghi Parking) during a day. Indeed, the strategy for using the capacity of different vehicles has details presented in some references. For instance, vehicles can be discharged up to 45% of the nominal capacity and

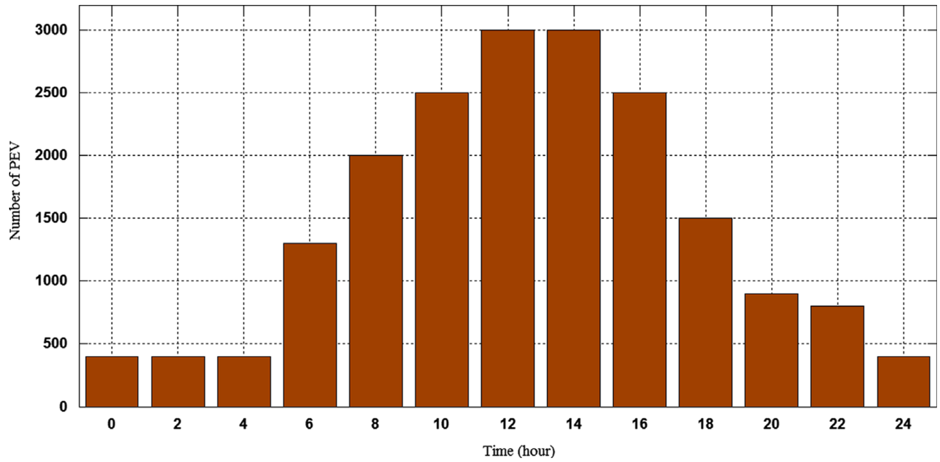

Fig. 6. Diagram for the number of parked cars in an usual parking lot in Tehran (Beihaghi Parking) during a day.

charged up to 80% of the nominal capacity (the lower band is considered for possible intra-city travels and the upper band is used for the fast charging of the vehicle battery) by the control system of the SP. Assuming $SOC^j(t)$ as the SOC of the jth parked vehicle in a SP at moment t, if $SOC^j(t) \le 45\%$, the jth vehicle can be charged in the next moment of $t+\Delta t$. If $SOC^j(t) \ge 80\%$, the jth vehicle can be discharged. And if $SOC^j(t) \in (45, 80)\,\%$, the jth vehicle has both the ability of being charged or discharged at the next moment.

In a typical SP, the most qualified vehicles for being charged/discharged are those with SOCs in the middle of the interval $(45, 80)$ i.e. $SOC = 65\%$. The reason is that these vehicles can be charged/discharged in a longer time period and thus the number of the vehicles involved in the charging/discharging process is reduced. Hence, a selection index is determined as follows:

$$PSI^j(t) = \left| SOC^j(t) - 62.5 \right| \tag{1}$$

where PSI is PEV Selecting Index. Afterwards, all the $PSIs$ related to the vehicles are sorted in an ascending order. Vehicles with smaller $PSI^j(t)$ are chosen to participate in the smoothing process. It is worth mentioning that if $USI(j) \ge 17.5$ (i.e. when $SOC^t(j) \le 45\%$ or $SOC^t(j) \ge 80\%$), the value of SOC is taken into account for the selection of vehicles.

Now assuming that the average capacity of a vehicle is 30 kWh and setting the 35% limitation for utilizing the capacities (i.e. SOC is between 45 to 80% and there are at least 10 parking lots in a city like Tehran), the capacity of all SPs in a smart distribution grid has been shown in Fig. 7.

In a large number of the researches on SPs, they are modeled by a huge battery with a determined capacity incorrectly. This method for modeling may be useful in some studies, but it is not acceptable in studies on smoothing the wind fluctuations; because different vehicles may have different batteries with different technologies or different capacities based on their sizes, and this should be considered in modeling. Furthermore, it is possible that vehicles do not have enough capacity for energy saving when wind energy saving is needed. Therefore the SP capacity should be modeled in a changeable manner in order to achieve results nearest to real ones.

5. Proposed configuration for future networks

Presented BESS configurations for a WPP are mostly categorized in three following groups:

(1) Distributed BESS in WPP side
(2) Aggregated BESS in WPP side
(3) Distributed BESS in load side (distribution network side)

Each configuration has been proposed for a specific application and thus has its own advantages and disadvantages. The distributed BESS configuration in WPP side is suitable when the WPP is small and just contains several WTGs. In such a small WPP, the output power of WTGs becomes smooth in the defined range by installing a single BESS for each WTG and thus the controlling of the WPP is easy. As the capacity and size of the WPP get larger into a medium or large WPP, the utilization of distributed BESS configuration in WPP side encounters two fundamental problems; the first issue is the considerable difference in the capacity and therefore in the cost of BESSs. For example for a 1000 MW WPP with an average power of 700 MW in alluded interval containing 200 WTGs with the capacity of 5 MW for each, assuming that fluctuation percentage is 60 and 14 for the output power of each single WTG and the whole WPP respectively, the battery capacity needed for utilizing distributed BESSs in WPP side is about 1.5 MWh for each WTG (200 turbines with 5 MW capacity, each turbine needs to generate about 3.5 MW in order to generate a total 700 MW power. Thus, the maximum turbine power is between 3.5 to 5 MW and the fluctuation will be 1.5 MW) and 300 MWh ($1.5\text{ MW} \times 200$) for the whole WPP. While, in the case of using aggregated BESS configuration in WPP side only about 100 MWh of ($700\text{ MW} \times 0.14$) battery is needed (the storage capacities have been considered in the worst situation). This 200 MWh difference is considerable.

The second issue is that in the case of using distributed BESS each WTG needs to be equipped with an extra control system for output power smoothing that means adding a minimum of 200 extra control systems for one WPP. While if the aggregated BESS configuration is utilized, only one control system will be needed. So it can be concluded that in the WPPs with average or large sizes, use of aggregated BESS in WPP side has more economical and control advantages rather than that of distributed BESS in WPP side.

The third proposed solution, utilizing distributed BESS configuration in load side, is very suitable for the smoothing process of WPF in small distribution networks like micro-grids. In this configuration, the output power of WPP is transmitted into the network. In this situation, the loads equipped with BESS perform the smoothing activity. It is evident that in this configuration enough knowledge on the loads and BESSs is required that means the network and thus the WPP should be small. Otherwise, the extension of the WPP leads to considerable fluctuations and even an insignificant disturbance may contribute in power quality issues of the network and result in the network collapse.

Currently, there is a growing tendency for using renewable energies specifically the wind energy. Regarding the significant

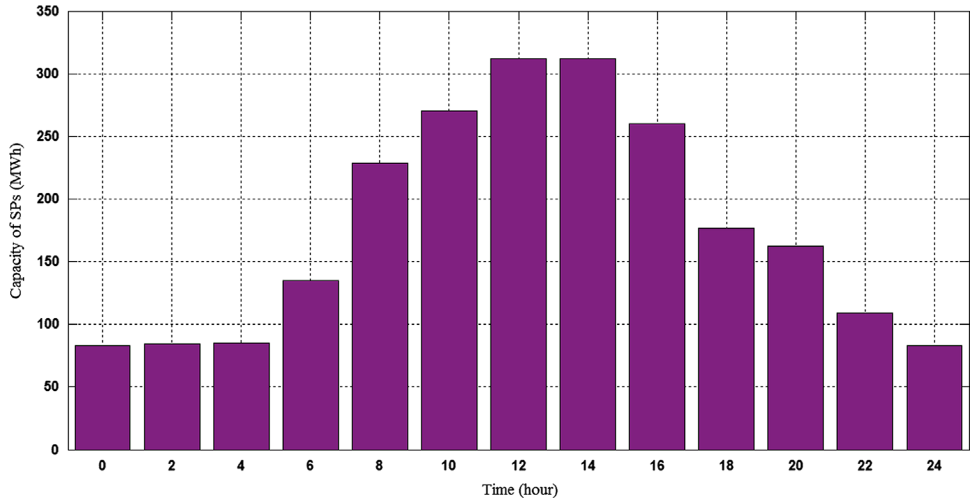

Fig. 7. The capacity of all SPs in a smart distribution grid.

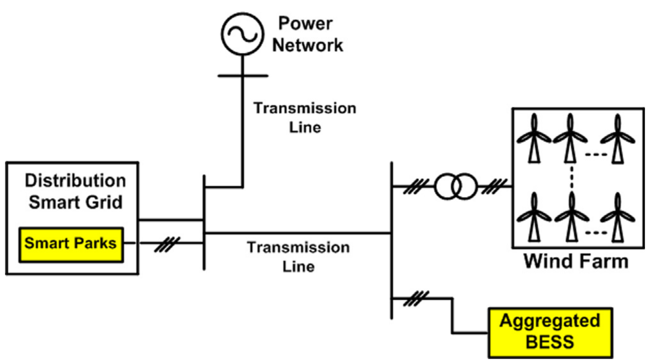

Fig. 8. The proposed configuration for a large WPP connected to a big smart grid.

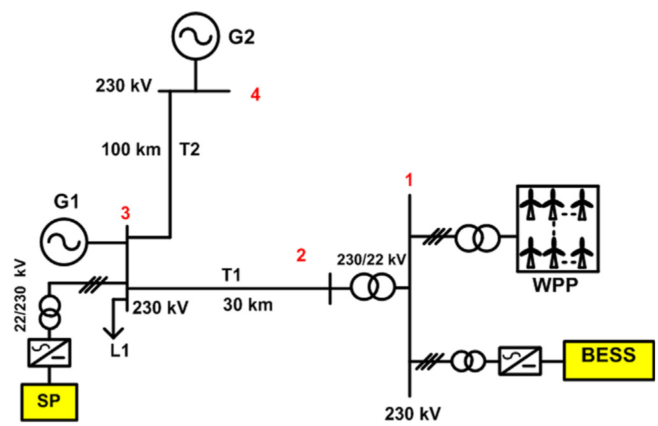

Fig. 9. The under-study power system.

reduction in WPF in the case of increasing the nominal capacity of WPPs, power system operators have been encouraged to create larger WPPs. However as mentioned before, the essential challenge in large WPPs is the high cost for their required BESSs. On the other hand, distribution networks are converting to smart grids. Smart grids also have very suitable advantages for different applications. Mentioned WPPs are connected to these smart distribution grids directly or by a transmission line with several to tens kilometers of length. So, using all the possible capabilities of these networks is necessary for the smoothing of WPF.

The proposed configuration for a large WPP connected to a big smart grid has been shown in Fig. 8.

This configuration utilizes aggregated BESS in WPP side along with aggregated BESS in load side (smart distribution grid). In fact, after calculating the WPF of WPP in this configuration, required capacity for batteries is determined. Then, near 30% of the needed capacity for aggregated BESS is installed in WPP side. Remaining required BESS capacity is provided by SPs. Although SPs seem to be distributed BESSs in network side at first, regarding the connection method of SPs the final BESS acts as an aggregated BESS in distribution network side. The idea for smoothing the WPF by using SPs is not merely suitable from two viewpoints; first, in spite of the large size and wideness of a distribution network, it is possible that the whole required capacity is not available in special situations or specific events. Second, a fault may occur in a SP that may result in temporary disconnection of the related park. This protection issue can influence the power quality of the network. Thus in both cases, aggregated BESS in WPP side can significantly prevent occurring these problems with the lowest cost.

Unlike other configurations in which the control is mostly performed at the WPP side (disregarding network requirements and capabilities), the smoothing process control in the proposed configuration is performed at the smart grid side. In this method, all the required information such as available power in WPP, storage capacity accessible for SPs, demand value for the network load, etc. is available and thus the optimum result can be achieved by use of an appropriate coordinated control system.

The comparison for simulation results between utilizing other configurations and proposed configuration in this paper has been illustrated in Section 6.3.3.2.

6. Modeling and simulations

6.1. Under-study power system

Fig. 9 shows the under-study power system in this paper. This system contains a large 20×10 WPP with 1000 MW generation capability. WTGs are speed varying DFIGs with 5 MW capacity. Additionally, the reference reactive power of DFIG convertors has been neglected in order to set the turbine power factor to 1. The required reactive power for induction generators is provided by their DC bus. This WPP has been connected to a 1200 MVA transformer and then to the common bus 2 by a 30 km transmission line. 200 MW power is given to L1 and the rest of the needed power is provided by generator G1. G1 and L1 represent distribution network.

Also, 500 MW power should be transmitted to the power network by transmission line T2. Similarly, the SP described in Section 4 has been connected to a 22/230 kV transformer to common bus 2. Also, 30 MWh BESS with SOC 50% in WPP side has been connected to bus 1 by a 22/230 kV transformer.

6.2. *Modeling of wind turbine and WPP*

A WTG with a wound rotor induction generator which is fed from both the stator and rotor sides has been shown in Fig. 10. The stator is directly connected to the network while a back to back convertor is used to connect the rotor. Modeling of different parts of the wind turbine system including wind, wind turbine, doubly fed induction generator and convertors are described in following.

6.2.1. *Modeling of the wind turbine*

Wind Turbine model includes aerodynamic model and rotary system model. Aerodynamic model of the turbine converts the wind speed to the mechanical torque. The mechanical torque resulted from the wind speed is calculated by

$$T_{WT}=\frac{1}{2}\rho R^2 V_W^2 C_p \tag{2}$$

where T_{WT} is the mechanical torque of the wind turbine, ρ is the air density [kg/m^3], R is the radius of turbine blades [m], V_W is the wind speed [m/s] and C_P is the performance coefficient.

The performance coefficient represents the percentage or part of the available energy of wind which can be achieved by the turbine. In addition to the aerodynamic form of the blade, C_P depends on other factors given in

$$C_p=f(\lambda,\theta)$$

$$\lambda=\frac{V_t}{V_W}=\frac{R\omega_t}{V_W} \tag{3}$$

where λ is the ratio of turbine blade tip speed to the wind speed, θ is the blade angle, V_t is the speed of turbine blade tip [m/s] and ω_t is the rotational speed of turbine blades [rad/s] [30]. The relation between the mechanical torque of turbine and the electrical torque of generator can be represented in

$$J_{WG}\frac{d\omega_r}{dt}=T_{WT}-T_e-D\omega_r \tag{4}$$

where J_{WG} is the total inertia moment of the wind turbine and the generator [kg m^2], ω_t is the rotor speed [rad/s], T_{WT} and T_e are mechanical torque of the turbine and electrical torque of the generator respectively [N m] and D is the friction coefficient [N m s/rad].

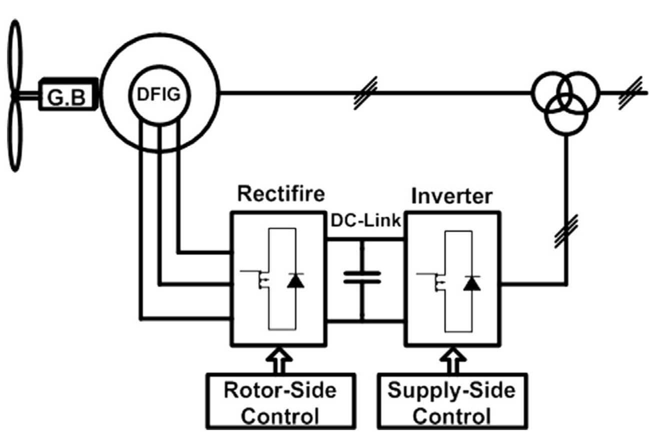

Fig. 10. A WTG with a wound rotor induction generator which is fed from both the stator and rotor sides.

6.2.2. *Modeling of induction generator and PWM convertor*

The wind power generators used in this paper are DFIGs. The stator is directly connected to the network while the rotor is connected via two back to back convertors. The rotor side convertor is a current-controlled voltage source inverter used to independently control the generator torque and the reactive power of the stator. The network side convertor is a PWM inverter which is used to transmit the active power to the DC bus and keep the capacitor voltage constant. In order to model the generator, *dq* rotational reference frame model is utilized while rotor and stator circuits are simulated in details. Without loss of generality, PWM convertors are simulated as a variable voltage source.

6.2.3. *Control system scheme*

The basics of DFIG wind turbine control system is on achieving the maximum power from the wind. Fig. 11 shows the power characteristic of a wind turbine in terms of the generator speed for different speeds. The performance range of the constant speed generator and also the performance range of the speed varying generator have been illustrated in the figure. As shown in Fig. 11 by changing the rotor speed in different wind speeds, the control system determines the optimum speed for rotor in order to extract the maximum wind power. The method presented in [31] has been used for controlling the DFIG wind turbine.

6.2.4. *Modeling of WPP*

After wind turbine generator modeling, WPP should be modeled. There are several different approaches for modeling the WPP including:

(1) WPP is modeled as a WTG with a power value equivalent to the whole WPP
(2) WPP is modeled considering the modeling for each single turbine
(3) Reduced modeling

Although WPP modeling as a single turbine is acceptable in some researches, it is completely inaccurate in researches related to the wind power smoothing. Because the output power of a single turbine may fluctuates up to near 60% of its nominal power while practical results show that the output power of a WPP fluctuates up to 14% of WPP nominal power. Thus, modeling by a single turbine results in about 60% fluctuations in output power of

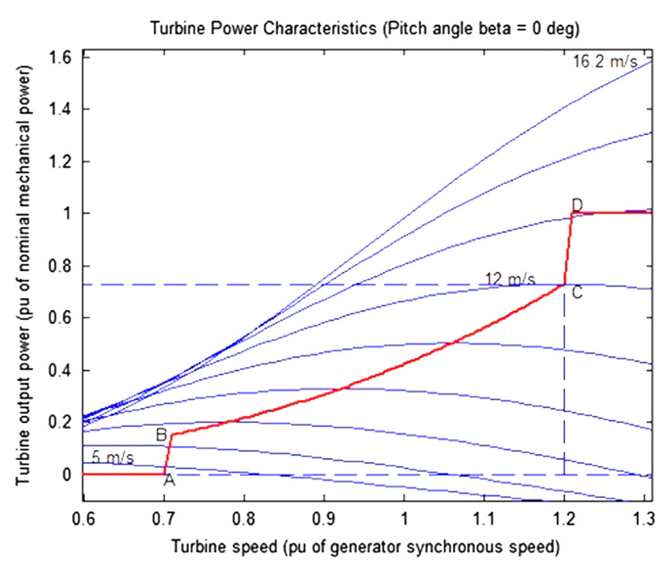

Fig. 11. Generator power versus wind speed and generator speed.

the WPP and it is not acceptable at all. Currently, the second approach i.e. turbine by turbine modeling is the most accurate modeling approach in smoothing studies. However, it may lead to some fundamental hardware problems. For example, for modeling a large WPP of size 20×10, a number of 200 DFIG turbines should be used in the modeling software. As the number of DFIGs is large, it is very time consuming to run such a simulation in the modeling software even by a fast computer. So it is really necessary to use a more suitable modeling approach.

Consider a 20×10 WPP with wind blowing from the right side (Fig. 12). The WPP has been considered in a square shape for simplifying although any desired form can be used in this model. The wind generator has been adjusted for 5 MW in order to simulate a 1000 MW WPP. The approximate distance between two adjacent turbines in the same row or column has been set to 700 m. According to Figs. 12 and 13 and considering the direction of wind, it is clear that turbines located in the same column have similar output power values. Therefore each column can be replaced by an equivalent wind turbine. It is obvious that the wind speed, which can be calculated by Fig. 14, is different in each column. So a WPP with 200 turbines can be modeled just by 10 turbines (it is evident that when the wind direction changes, just the method of modeling changes). In this approach the simulation speed is much higher than that of turbine by turbine approach while the accuracy of simulations remains acceptable as well.

WTGs are usually influenced by two kinds of wind fluctuations: low fluctuations and high fluctuations. During high fluctuations, the wind speed deviates $\pm 35\ \%$ of the average speed while the speed deviation is about 10% during the low fluctuations. In this paper high fluctuations have been taken into account. Also, the average wind speed considered in the simulations is 14 m/s. The wind sample selected from [32] has been shown in Fig. 1.

6.2.5. Modeling of SP

As mentioned in Section 5, although considering SPs as very huge batteries is a reasonable assumption, their modeling as a battery with a specified capacity is completely incorrect because of several reasons: (1) the initial charging of vehicles is different from each other. It is possible that a PEV with 10% SOC enters the park and as its SOC is under 45%, the control system can charge it to 80% and obviously it does not have the permission to take power from this vehicle at first. Contrarily, maybe a PEV with 80% initial SOC enters the park and thus the control system is permitted to take its power up to 45% and increase the battery SOC only up to 20% in the best conditions. So, it can be concluded that in smart park studies two diagrams are needed in each moment; charging diagram and discharging diagram. (2) The number of PEVs is a random variable and thus the SOC of smart parks is changeable too. Additionally as illustrated in Fig. 6, the number of PEVs is different during different hours of the day. Therefore, charging and discharging diagrams of SPs should be considered variable rather than considering constant or average values for them. (3) Depending on their location in the city, the behavior of SPs is different. Fig. 15 shows the capacity of SPs in the middle of the day for 1000 s.

6.3. Proposed approach

6.3.1. System variables

In order to smooth wind power fluctuations, system variables and their importance should be determined first. Variables existing in the under-study system are: WPP output power (P_{WF}), power transmitted to the network (P_T), required power consumed in transmission network (P_L), SPs initial Status Of Charging (SOC_{SP}) and WPP BESS initial status of charging (SOC_{BESS}). In fact, all the mentioned variables are stochastic. Some of them like $P_{WF,}$ have extended changing rates and some others like $P_{T,}$ have smaller changing ranges. Assuming P_{SP}

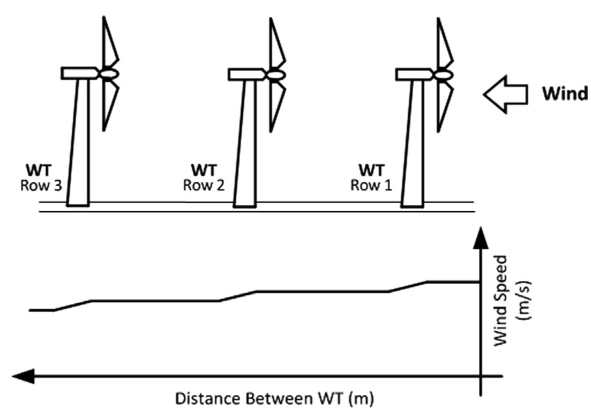

Fig. 13. The aerodynamics shadow effect on decreasing the wind speed.

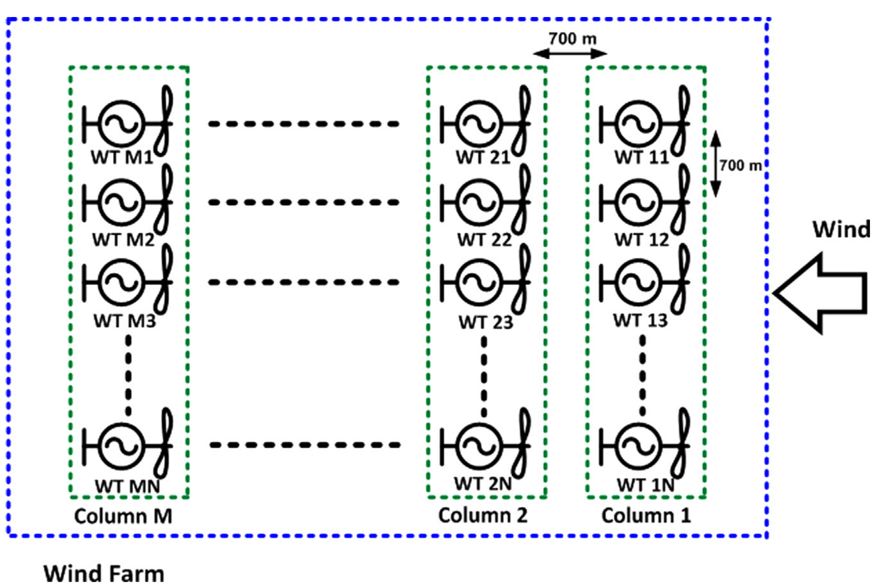

Fig. 12. A 20×10 WPP with wind blowing from the right side.

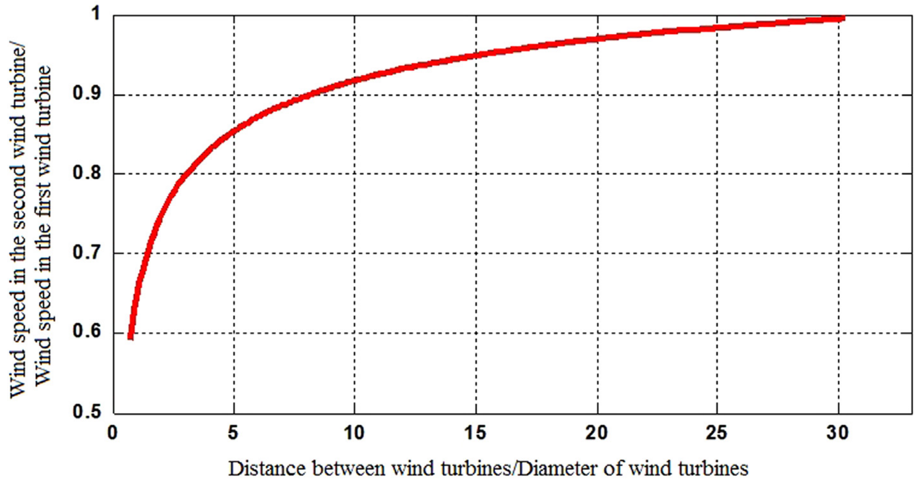

Fig. 14. Wind speed in two different rows of WTGs.

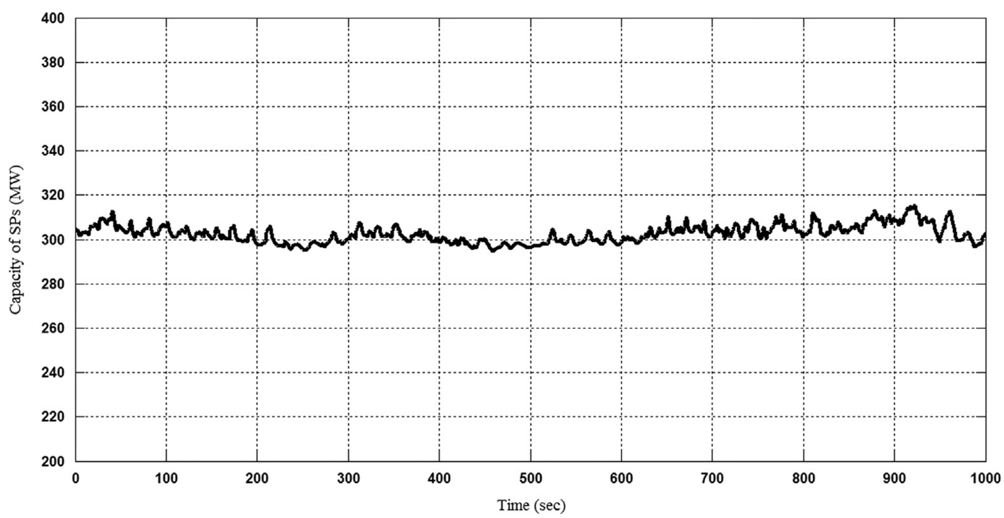

Fig. 15. Capacity of SPs in the middle of the day.

and P_{BESS} represent the instantaneous power of SPs and WPP BESS respectively, Fig. 16 shows the relation between variables. Their mathematical relation can also be presented as in

$$P_{WF} - P_L - P_T + \alpha P_{SP} + \beta P_{BESS} = 0 \tag{5}$$

Because the value of energy extracting or saving by SPs and WPP BESS is not pre-specified, two additional parameters are added to the system parameters as seen in Eq. (4). By solving the above equation, variables α and β can be calculated. For this reason a coordinated control system is needed. As the purpose of this paper is to introduce a suitable configuration for WPP BESS and smart grids rather than presenting the coordinated control system, some simplifying assumptions are considered (the assumptions do not change the problem generality). It is assumed that the instantaneous power of the transmission line is a constant value (500 MW here). The second assumption is that the power consumed by transmission network is considered constant during the related under-study time. Now, the issue is that the energy storage devices (SPs and WPP BESS) should provide or take the difference value between the generated power of WPP and the required power for distribution and transmission networks.

As the purpose of installation of aggregated BESS in WPP side is to support SPs in some situations such as diminishing their capacity or unwanted fault occurrence, the coordinated control system performs the smoothing activity in all situations by use of the SP capacity at first. The aggregated BESS in WPP side is used when SPs are unable to completely smooth the WPF. For this reason, it is assumed that the initial SOC of WPP side BESS is 50%, i.e. its ability for power charging and discharging is equal.

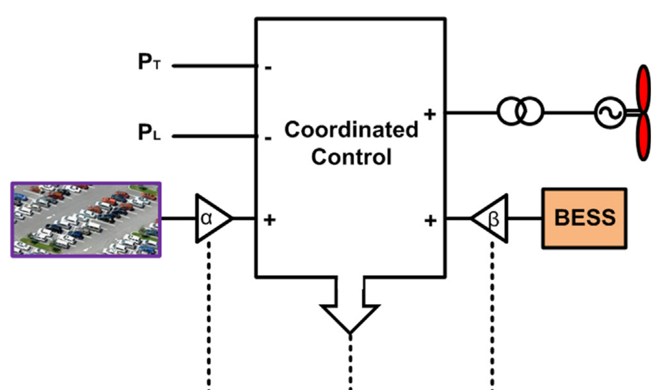

Fig. 16. The relation between system variables.

6.3.2. Smoothing power fluctuations by proposed configuration

Fig. 17-a shows the maximum power generated by WPP in the test network shown in Fig. 9 for a wind sample with an average speed of 14 m/s (Fig. 1) in a time period of 600 s. In addition, the total power value of SPs without any connection to the common bus has been illustrated in Fig. 17-b. Assuming that the SOC of WPP side BESS is 50%, its power curve has been determined in Fig. 17-c.

After connecting the WPP to the network via line T1, it is supposed to finally transmit 500 MW and 200 MW smoothed power values to the transmission network and distribution network respectively. As explained previously, at first the smoothing is performed by SPs and then the WPP BESS is used if required. Considering $\beta=0$ and determining a controllable α in this simu;lation, the smoothing activity is performed only by SPs. Fig. 18 shows the power transmitted to the power network, the power transmitted to the distribution network and the exchanged power of the SPs (positive and negative values represent discharging and charging) respectively.

According to Fig. 18, it is evident that the fluctuation smoothing for a large WPP has been performed accurately by proposed configuration approach.

6.3.3. Comparing proposed configuration approach with other configurations

6.3.3.1. WPP side distributed configuration of BESS. According to the explanation in Section 5 about the fluctuation of a single WTG, a 1.5 MWh battery is needed for smoothing the output power of a 5MW WTG. Assuming that 1.5 MWh batteries have been installed for every single WTG in the under-study network, the output power of the WPP before and after the smoothing has been shown in Fig. 19.

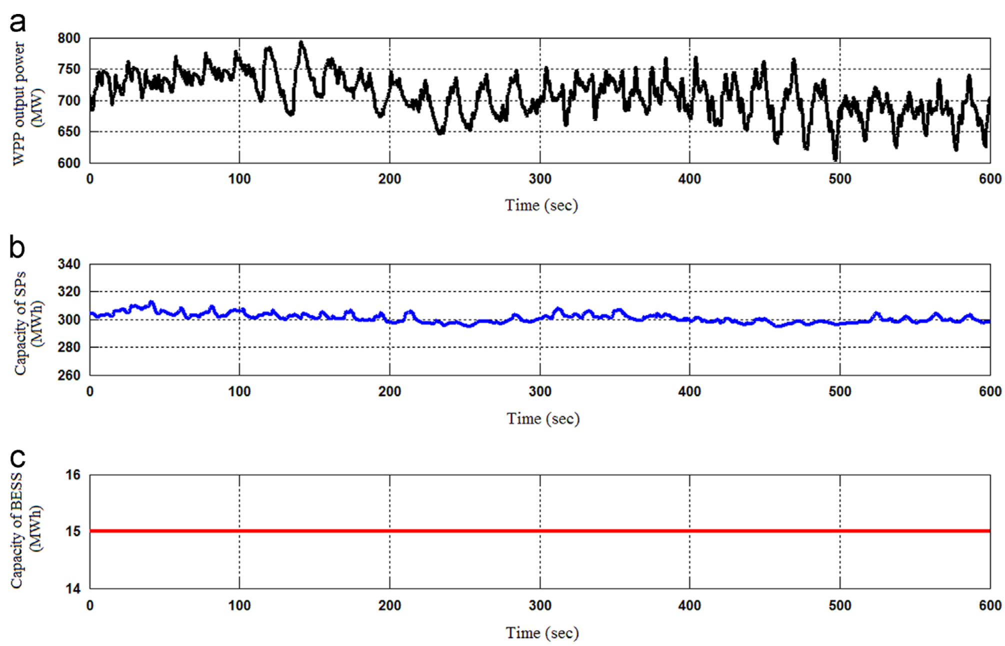

Fig. 17. (a) WPP output power (b) capacity of SPs and (c) capacity of BESS.

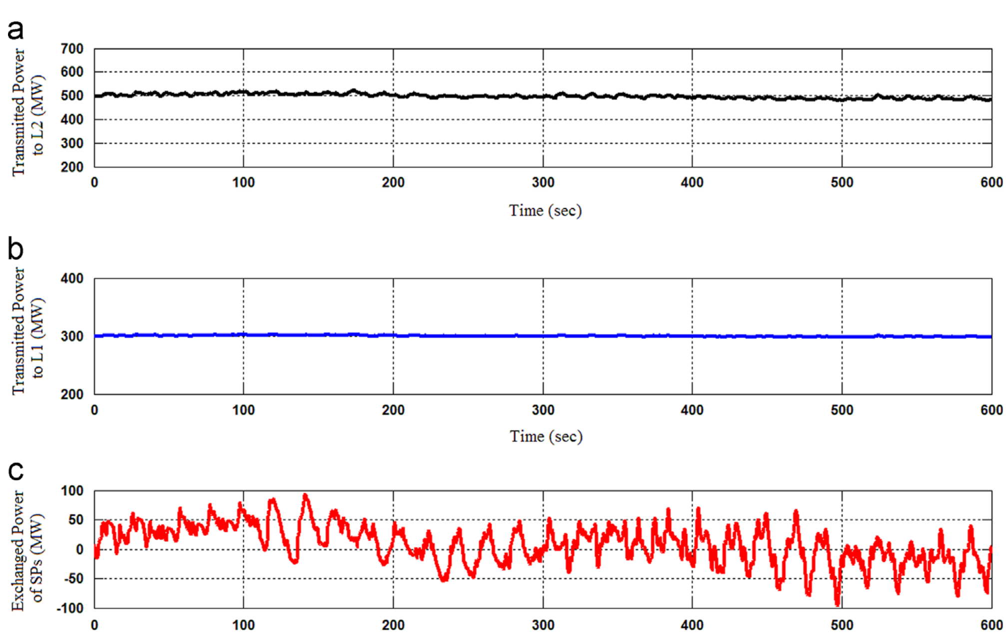

Fig. 18. (a) Transmitted power to T2 (b) transmitted power to L1 and (c) exchanged power of SPs.

It is observable that the WPP output power has been completely smoothed. This accurate smoothing has been executed by using 200 of 1.5 MWh batteries i.e. a battery with a capacity of about 300 MWh. Although the final results in the smoothing of WPF in this method and the approach proposed in this paper are the same, using distributed BESS is not economical at all. The comparison from the controlling viewpoint has been described previously.

6.3.3.2. WPP side aggregated configuration of BESS. As illustrated in Fig. 2-b, WPF of the WPP in the test network is near 14% of the WPP nominal power. So, in order to completely smooth the fluctuations using one aggregated battery in WPP side, a 140 MWh battery is required. Considering the installation of this battery for running the simulations, the output power of WPP before and after the smoothing has been shown in Fig. 20. The resulted smoothing activity using this configuration is acceptable too. Although it has more economical justification compared with WPP side distributed BESS, the priority for selecting it is lower than the proposed configuration in this paper.

6.3.4. *Effect of the fault occurrence in SPs*

Assume that in simulations of Section 6.3.3.2 a fault occurs in SPs and the protection system disconnects half the parks from the distribution network. The total power of SPs without any connection to the common bus has been shown in Fig. 21. It can be observed that fault occurs at $t=300$ s. In this situation, SP will not be capable of complete smoothing by itself any longer and thus the capacity of WPP BESS is used to help the smoothing process. In other words, α is equals to 1 and the instantaneous value of β is adjusted by the coordinated control system. Fig. 22 shows the WPP output power, SPs exchanged power and WPP BESS exchanged power respectively (the power transmitted to transmission and distribution networks has no fluctuations and it is not considered again).

6.3.5. *Effect of capacity changes during a day*

In manuscripts, SPs are considered a huge battery with a determined capacity for modeling. Although it is more economical to use SPs merely, results of this paper demonstrate that it can make serious problems for the network. For instance, the power of

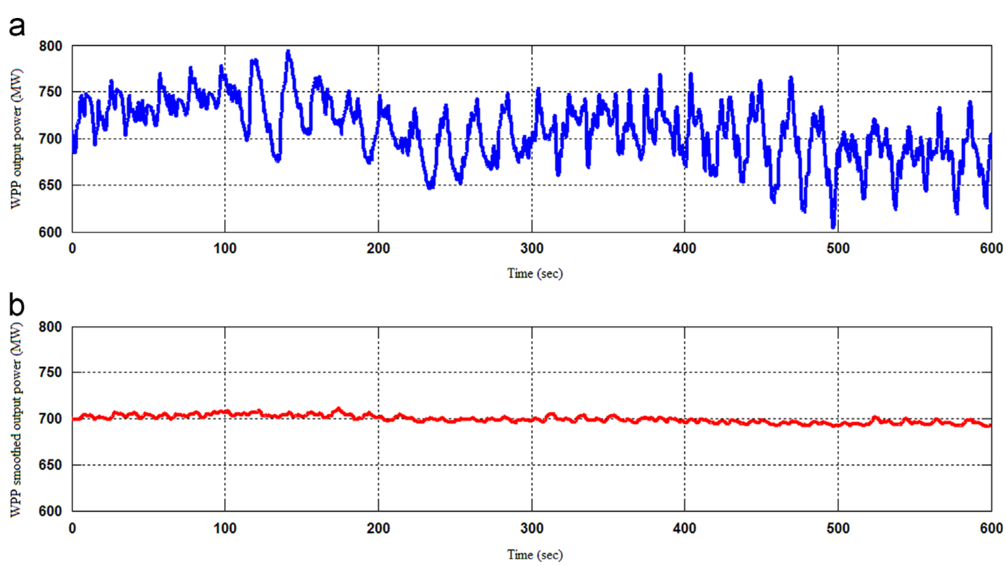

Fig. 19. (a) WPP output power: (a) before smoothing and (b) after smoothing.

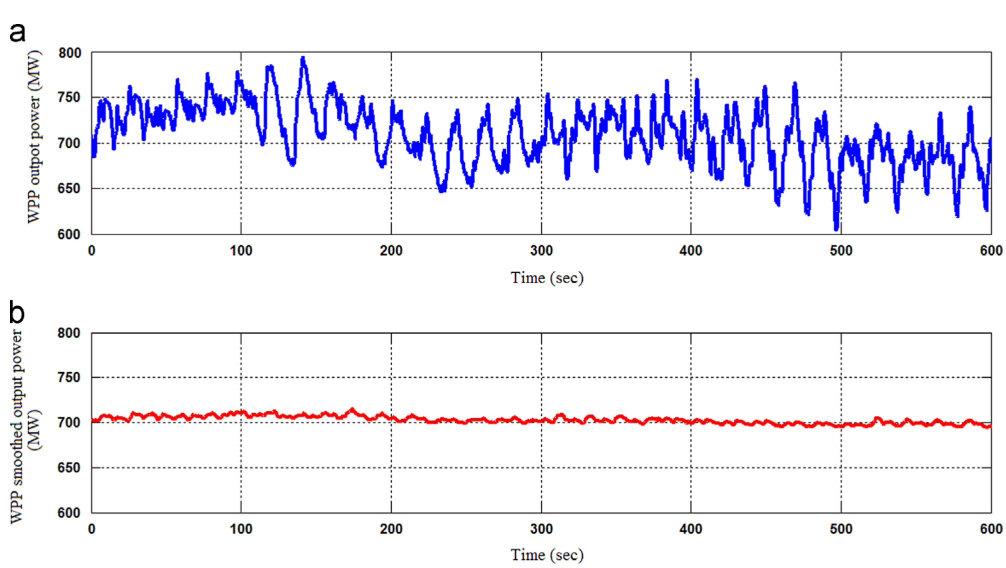

Fig. 20. WPP output power: (a) before smoothing and (b) after smoothing.

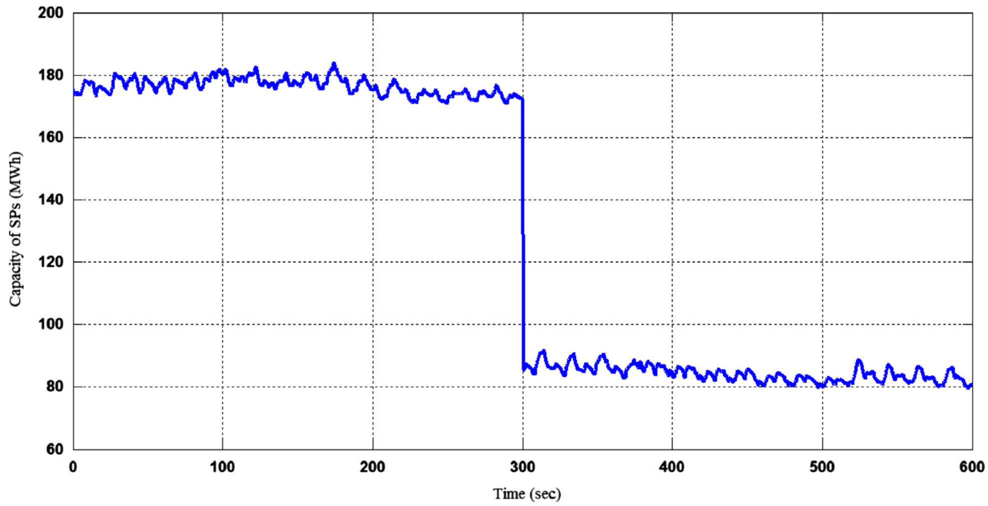

Fig. 21. The total power of SPs; at $t=300$ a fault occurs in bus SPs and half of them disconnect.

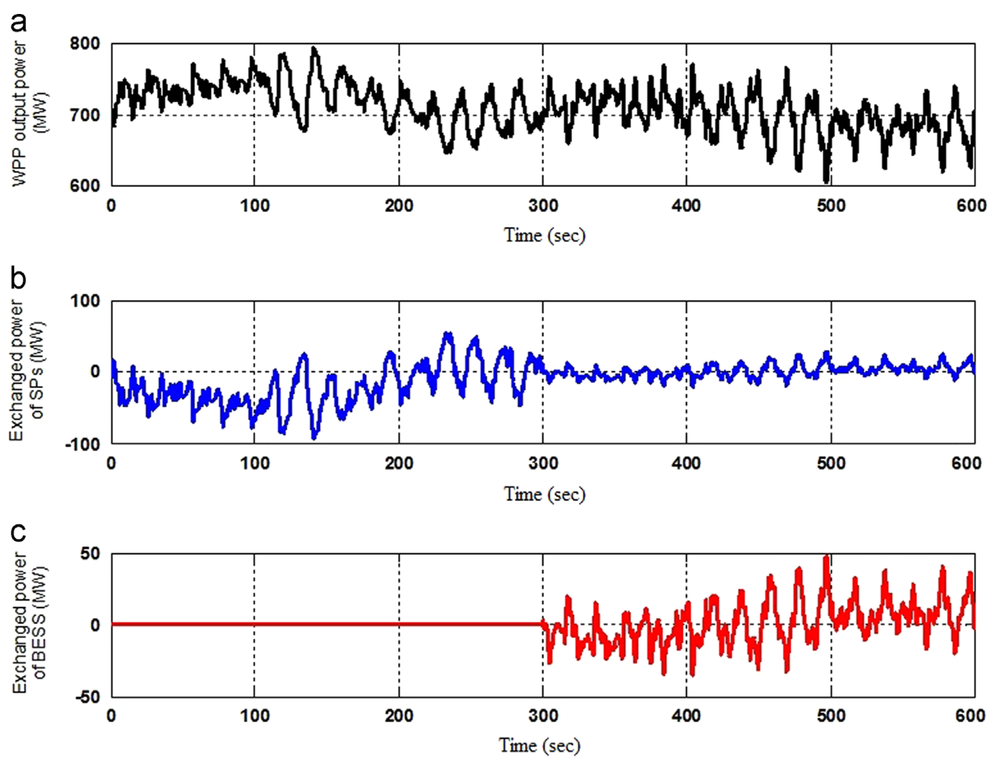

Fig. 22. (a) WPP output power (b) SPs exchanged power and (c) BESS exchanged power.

SPs may change based on the number of vehicles and the initial SOC of vehicles. In other words, SP should be modeled as a battery with variable power (with stochastic nature). As another study, a simulation in a time interval of 600 s is performed for the test network in late hours of the night. Maximum power generated by the WPP, SPs exchanged power in late hours of the night and WPP BESS exchanged power (with no connection to the network) have been shown in Fig. 23.

In this situation the use of SP capacity is not adequate for complete smoothing of WPP output power fluctuations. In this case, $\alpha=1$ and the value of β that may reach to 1 is adjusted by the coordinated control system. Fig. 24 demonstrates changes in the SP power and the WPP BESS power respectively. The transmitted power in the network and the distribution network power are equal to the requested value without any fluctuations. This verifies that utilizing SPs is not enough for smoothing the fluctuations.

It is worth mentioning two points:

(a) the minimum capacity required for WPP side aggregated BESS is considered equal to the required BESS (in WPP side) in the worst situations like late hours of the night, fault occurrence and SP losses when the capacity of SPs is in its minimum value.
(b) Although in some metropolitan cities, the huge capacity of SPs can handle WPP power fluctuation issues lonely, it is still necessary to install the aggregated BESS in WPP side because of mentioned protection reasons.

6.3.6. *Economic evaluation*

The survey on the performance of the proposed approach in previous sections was conducted for a time period of 600 s (10 min).

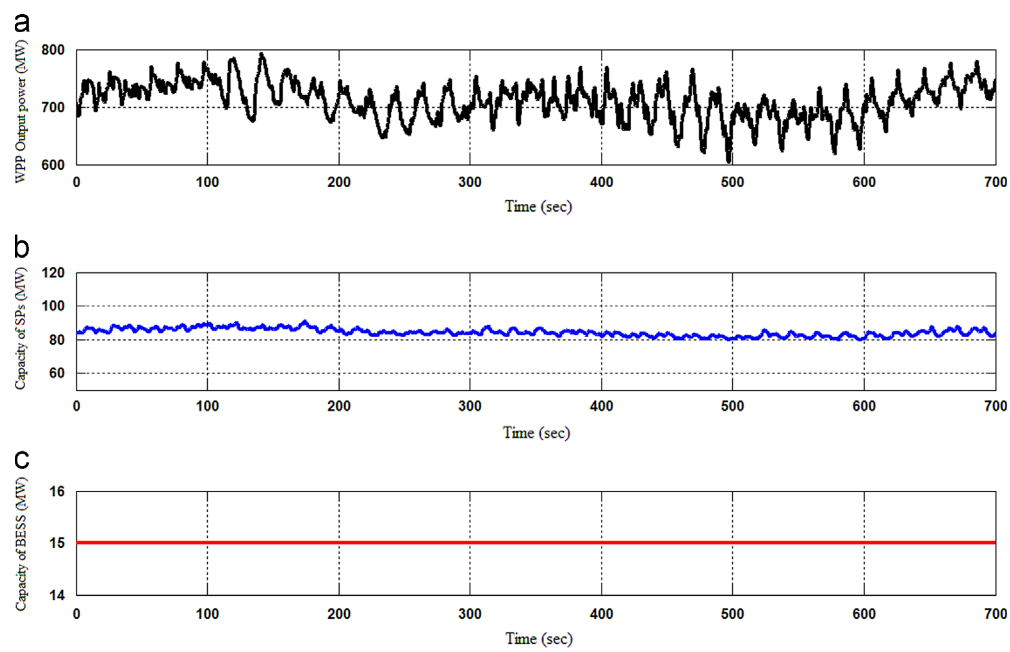

Fig. 23. (a) WPP output power (b) capacity of SPs and (c) capacity of BESS.

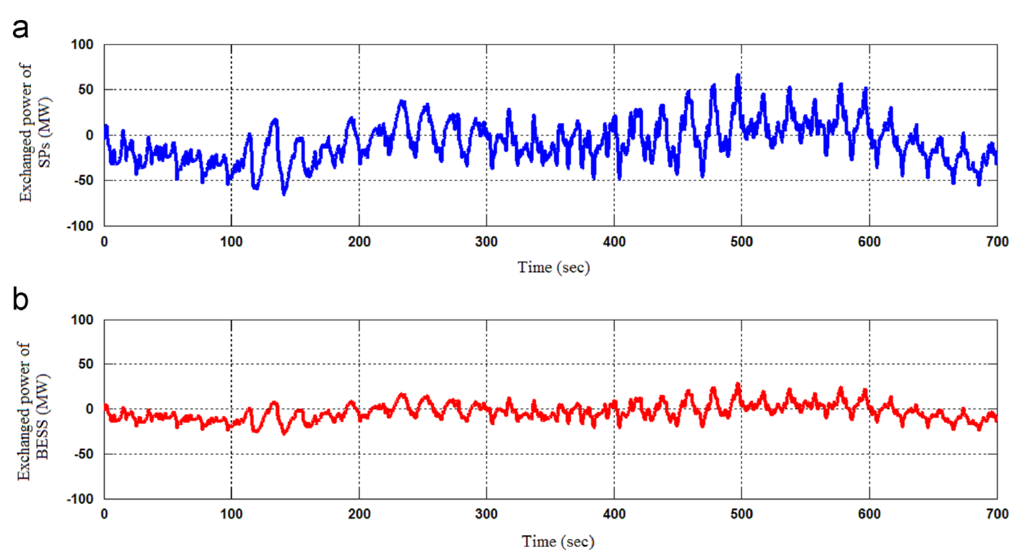

Fig. 24. (a) Exchanged power of SPs and (b) exchanged power of BESS.

For simplicity, the transmitted power to the power grid and to the distribution network in this short period was considered to be constant. Since the wind speed is changing during the day, the output power of WTGs and thus the output power of the wind farm suffers so much change. In this situation, the assumption of transmitting constant power to the power grid and to the distribution network is not acceptable. Utilities apply some requirements on renewable resources like WPP which determine the permissible power fluctuations. Different requirements have been considered in different countries, most of them alluded in [33]. If the fluctuations of WPPs remain within the permissible range, utilities can easily control remained fluctuations at no extra cost. As in [16], the requirement for the wind farm power ramp is considered so that the maximum change of the wind farm output power (the injected power to the power grid) in every 10-min window is not more than 7% of the wind farm nominal power.

In order to compare the initial investment cost of the BESS in the proposed configuration with other configurations, simulations should be analyzed in a period of several hours to several days. Real wind patterns of Shanxi Province, China with a sampling time of 5 s are used in this study. Patterns are applied on the under-study wind farm of Section 6.1. Fig. 25 shows unsmoothed (with no connection to the network) and smoothed wind farm output power (regarding the requirements) for ten-hour duration. The smoothed power is injected to the transmission and distribution networks and its difference is provided by the utility. As illustrated in Fig. 25, fluctuation of the smoothed power is considerably less than that of the unsmoothed power.

In the following, real data of 7 different days are applied to the test network described in Section 6.1 and then considering the selected requirements, the smoothing activity is performed by distributed BESS, aggregated BESS and the proposed approaches, respectively. Simulation results are given in Table 1. Enormous BESSs are practically composed of N BESS Units with smaller capacities. The capacity of each BESS unit is equal to 1.5 MWh. In distributed BESS configuration the value of N is considered 200

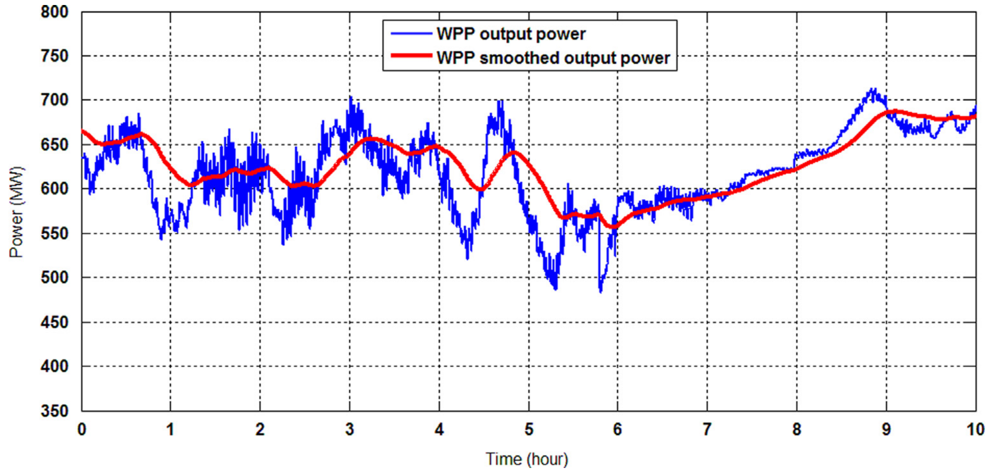

Fig. 25. Waveforms of smoothed and unsmoothed WPP output power.

Table 1
Comparison of BESS capacity allocation in the proposed configuration with traditional configurations.

Time	Distributed BESS		Aggregated BESS		Proposed approach	
	Capacity (MWh)	Units (N)	Capacity (MWh)	Units (N)	Capacity (MWh)	Units (N)
Day 1	225.1257	200	137.2258	95	24.7448	19
Day 2	221.5513	200	133.6413	93	20.2470	17
Day 3	216.6217	200	128.7892	87	19.3128	16
Day 4	238.7426	200	145.1574	101	26.1320	23
Day 5	220.1368	200	133.6127	93	20.9123	17
Day 6	233.4950	200	141.8138	99	25.6748	21
Day 7	218.3187	200	130.3021	90	19.1530	15

for the under-study wind farm. This is because all the WTGs need to be equipped with BESS in this configuration. However, the *N* value in the aggregated BESS approach and the proposed approach is achieved by the simulation results. There are two columns related to each approach in Table 1, one for the total charging/discharging capacity in MWh and the other one for the number of required BESS Units. The initial capacity of each BESS Unit is equal for all three approaches and is considered 50%. According to Table 1, distributed BESS approach always needs 200 units while the aggregated BESS approach and the proposed approach need 101 units and 23 units in the worst situation (Day 4) respectively. According to the investigation results in [34], lithium-ion BESSs have an average installed price of U.S $500/kWh in the most profitable situation. Hence, the BESS investment cost equals to 150, 75.75 and 17.25 million dollars for distributed BESS, aggregated BESS and the proposed approach respectively. It is clear that the investment cost in the proposed approach is extremely less than that in other traditional approaches.

7. Conclusion

Random nature of the wind speed along with utilizing speed varying wind turbine generators in WPPs makes the output power of the WPP fluctuate. As the WPP capacity increases, the effect of WPP power fluctuations on the system stability becomes more significant. A suitable solution for smoothing the fluctuations is to use energy storage resources like batteries. However, the costly initial investment of batteries is an essential challenge for operators. Additionally, in a WPP the place where batteries are located has considerable direct effect on their required capacity and thus on the initial investment cost. The optimum configuration is the one that contributes in reducing investment costs of energy storage resources in addition to accurate smoothing of WPP power fluctuations. In this paper, at first the existing configurations for installing batteries in WPPs are investigated and then a suitable configuration which significantly reduces the batteries investment cost is proposed. Additionally, the wind power fluctuation of a high power large WPP connected to a smart distribution grid is smoothed simultaneously. In order to achieve these two purposes, smart parks (as high capacity storage resources) in smart grid side and one aggregated BESS with limited capacity in WPP side are used. This optimum configuration decreases use of energy storage resources in large WPPs and thus the costs are significantly reduced compared to other existing configurations. The proposed scheme can perform the smoothing activity accurately even in the worst unusual situations (in which the smart parks capacity is in its lowest value) such as late hours of the night, fault occurrence and smart parks losses. Simulation results show that the proposed approach is effective to smooth wind power fluctuation with the least investment cost of the BESS. Also, the accurate method of modeling for WPPs and smart parks in wind power fluctuations smoothing studies is described in this paper.

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